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**BEAMR - AN INTERACTIVE  
GRAPHIC COMPUTER PROGRAM  
FOR DESIGN OF CHARGED-PARTICLE  
BEAM TRANSPORT SYSTEMS**

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# **BEAMR - AN INTERACTIVE GRAPHIC COMPUTER PROGRAM FOR DESIGN OF CHARGED-PARTICLE BEAM TRANSPORT SYSTEMS**

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## **SUMMARY**

A computer program is presented which calculates the characteristics of a charged-particle beam as it is transported through a sequence of focusing and bending magnets. The maximum dimensions of the beam envelope normal to the transport system axis are continuously plotted on an oscilloscope as a function of distance along the axis. Provision is made to iterate the calculation by changing the types of magnets, their positions, and their field strengths. The program is especially useful for transport system design studies because of the ease and rapidity of altering parameters from panel switches. A typical calculation for a system with eight elements is completed in less than 10 seconds. A version containing more-detailed printed output but no oscilloscope display is also presented.

## **INTRODUCTION**

Designing a beam-handling system for the experimental facility associated with the modified NASA Lewis 60-inch cyclotron required that we calculate the effect of each proposed beam-handling element upon the beam properties. In fact, calculating the properties of the beam at each point in the system from the source (the cyclotron) to the target was necessary in order to determine not only the characteristics and physical locations of the beam-handling equipment, but also the field-settings which would provide the highest quality beam for a particular experiment after the hardware had been placed.

Four characteristics of a charged-particle beam are most significant to a prospective user. The first is the spatial extent of the beam ( $x, y$ ), both as it traverses the beam-handling system and as it arrives at the target. Closely related to the spatial extent, and for many experiments of equal importance, is the divergence of the beam ( $x', y'$ ) when it reaches the target. In addition, it is often necessary to

know the spread in momentum  $\Delta p$  of the particles contained in the beam. For experiments which involve timing, it is also necessary to have some knowledge of the spread in time (anisochronicity  $\Delta \lambda$ ) of the incident beam. Thus, a complete description of the beam, at least for purposes of any experiment presently anticipated, requires six dimensions.

## MATHEMATICAL METHOD

### Single Charged Particle

The basic assumption underlying all calculations performed by the present program is that the transformation of the coordinates of a particle at any point in the system to a later point is linear (i.e., the calculations are carried out to first order). The transformation may be written

$$\bar{X}_1 = \mathcal{T} \bar{X}_0$$

where  $\bar{X}_1$  is a six-dimensional vector whose components are the coordinates of a particle at time (or position) 1,  $\bar{X}_0$  is a vector comprised of the set of these same coordinates at time (or position) 0, and  $\mathcal{T}$  is the transformation matrix. The scalar coordinates selected for description of a single particle traversing the beam-handling system are

- x distance of particle from system centerline in the horizontal plane
- x' angle between system centerline and projection of particle momentum onto horizontal plane;  $x' = dx/dz$ , where z is coordinate along system axis
- $\Delta p$  deviation of particle momentum from that of particle which would traverse system centerline
- $\Delta \lambda$  deviation in distance traveled from that of particle traversing system centerline
- y distance of particle from system centerline in vertical plane
- y' angle between system centerline and projection of particle momentum onto vertical plane; y' is analogous to x'

The coordinates x, x', y, y' are shown graphically in figure 1.

The problem then becomes one of determining how each type of beam-handling element encountered will transform the particle coordinates (i.e., what is the nature

of the transformation matrix  $\mathcal{T}$  for each piece of hardware). These matrices are well known (refs. 1 to 3) and are easily constructed. For the convenience of the reader, they are summarized here as follows:

(1) For a field-free region (drift space) of length  $L$ , the  $\mathcal{T}$  matrix is given by

$$\mathcal{T} = \begin{pmatrix} 1 & L & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & L \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Hence,  $\bar{\mathbf{X}}_1 = \mathcal{T}\bar{\mathbf{X}}_0$  is equivalent to the scalar equations

$$x_1 = x_0 + Lx'_0$$

$$x'_1 = x'_0$$

$$\Delta p_1 = \Delta p_0$$

$$\Delta\lambda_1 = \Delta\lambda_0$$

$$y_1 = y_0 + Ly'_0$$

$$y'_1 = y'_0$$

(2) For a uniform-field magnet, the  $\mathcal{T}$  matrix is given by

$\frac{\cos(\varphi - \alpha)}{\cos \alpha}$	$R \sin \varphi$	$R(1 - \cos \varphi)$	0	0	0
$\frac{\sin(\varphi - \alpha - \beta)}{R \cos \alpha \cos \beta}$	$\frac{\cos(\varphi - \beta)}{\cos \beta}$	$\sin \varphi + \tan \beta(1 - \cos \varphi)$	0	0	0
0	0	1	0	0	0
$\sin \varphi + \tan \alpha(1 - \cos \varphi)$	$R(1 - \cos \varphi)$	$R(\varphi - \sin \varphi)$	1	0	0
0	0	0	0	$1 - \varphi \tan \alpha$	$R\varphi$
0	0	0	0	$-\tan \alpha - \tan \beta + \varphi \tan \alpha \tan \beta$	$1 - \varphi \tan \beta$

where  $R$ ,  $\varphi$ ,  $\alpha$ , and  $\beta$  are magnet dimensions, defined by figure 2.

(3) For a quadrupole lens - horizontally defocusing, vertically focusing (ref. 2), the matrix is given by

$\cosh(kL)$	$\frac{1}{k} \sinh(kL)$	0	0	0	0
$k \sinh(kL)$	$\cosh(kL)$	0	0	0	0
0	0	1	0	0	0
0	0	0	1	0	0
0	0	0	0	$\cos(kL)$	$\frac{1}{k} \sin(kL)$
0	0	0	0	$-k \sin(kL)$	$\cos(kL)$

where  $L$  is the effective length of the lens, and  $k$  is the focusing strength, related to the magnetic field gradient  $G$  by

$$k^2 = eG/p$$

where  $p/e$  is the magnetic rigidity. If  $p/e$  is expressed in kilogauss-inches, and  $G$  in kilogauss/inches, then  $k$  has the dimensions  $(in.)^{-1}$ .

(4) For a quadrupole lens - horizontally focusing, vertically defocusing (ref. 2), the matrix is given by

$\cos(kL)$	$\frac{1}{k} \sin(kL)$	0	0	0	0
$-k \sin(kL)$	$\cos(kL)$	0	0	0	0
0	0	1	0	0	0
0	0	0	1	0	0
0	0	0	0	$\cosh(kL)$	$\frac{1}{k} \sinh(kL)$
0	0	0	0	$k \sinh(kL)$	$\cosh(kL)$

(5) For a rotation about the beam axis (ref. 3), the matrix is given by

$\cos \theta$	0	0	0	$\sin \theta$	0
0	$\cos \theta$	0	0	0	$\sin \theta$
0	0	1	0	0	0
0	0	0	1	0	0
$-\sin \theta$	0	0	0	$\cos \theta$	0
0	$-\sin \theta$	0	0	0	$\cos \theta$

where  $\theta$  is the angle of rotation - positive for a clockwise (looking downstream) rotation, negative for counterclockwise (looking downstream) rotation. The rotations are mathematical operations in the program which rotate the beam in order to use a single bending magnet matrix for all physical orientations of the magnets.

### Beam of Particles

The formulation just given is sufficient for the calculation of the trajectory of a single charged particle through a system of magnets. However, the physical entity to be treated is a collection of particles with a spread in initial coordinates. In one dimension, for example, the beam would occupy a certain region of the  $x, x'$  space.

This is most conveniently represented by a phase-space ellipse, as shown in figure 3. At a waist, or spatial minimum, the phase-space ellipse becomes upright. As the beam traverses a field-free region, for example, the ellipse becomes skewed, as shown by the third ellipse in figure 3.

The formulation of the transformation of a beam envelope or ellipse is again most easily accomplished by means of a matrix formalism (ref. 3). If the beam envelope at a time (or position) 0 is given by

$$axx + bxx' + cx'x' = 1 \quad (1)$$

then the envelope at time (or position) 1 will be given by a similar ellipse but with coefficients  $a'$ ,  $b'$ , and  $c'$ . In matrix form, equation (1) may be written

$$\begin{pmatrix} x & x' \end{pmatrix} \begin{pmatrix} a & b/2 \\ b/2 & c \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix} = 1$$

or

$$\bar{x}^T \mathcal{S}^{-1} \bar{x} = 1$$

It is easily shown that a matrix  $\mathcal{T}$  which transforms the coordinates  $x, x'$  to new values will transform the matrix  $\mathcal{S}$  as

$$\mathcal{S}(2) = \mathcal{T}\mathcal{S}(1)\mathcal{T}^T$$

Furthermore, the physical dimensions of the beam are related to the diagonal elements of the  $\mathcal{S}$  matrix:

$$x_{\max} = (S_{11})^{1/2}$$

$$x'_{\max} = (S_{22})^{1/2}$$

The generalization of the method for a six-dimensional problem is straightforward.

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The final transport to the target is accomplished by making the target element equivalent to a rotation of zero degrees preceded by the actual drift length.

The program flow is diagrammed in figure 4. Initially, the input parameters are typed in for the following quantities (see the section Input Values for details):

- (1) The initial beam vector, XMAX
- (2) The number of elements, JMAX
- (3) The parameters for each element

The parameters XMAX and JMAX are read in by the main program. Each set of parameters for an element is read in by the subroutine REED; the transport matrix for that element is written, if desired, by the subroutine RITE. The matrices are calculated by the subroutines MAG, QUAD, and ROT.

For the transport calculation, the index J is incremented by 1 until JMAX is reached. For a given J, the subroutine DRIFT calculates the values of  $x_{max}$ ,  $y_{max}$  in the drift space. The total transport matrix  $\mathcal{T}$ , representing the entire system up to the given point, is updated after the return from DRIFT. The transport matrix is again updated by MATMLT, which multiplies  $\mathcal{T}$  by the proper element matrix; and these values of the  $\mathcal{T}$  matrix (at the end of an element) are saved.

At the end of the calculation, the DSPLA subroutine displays the results and pauses (Pause 2) until a further command is entered from the panel (fig. 5) or until the light-pen switch is pressed. The oscilloscope display (fig. 6) includes points representing  $x_{max}$  and  $y_{max}$  as a function of distance z from the entrance of the transport system (see the section Display). If the light-pen is held over a selected point and the pen switch depressed (initiating a call to the subroutine LANDT), the  $\mathcal{T}$  matrix and the beam vector XMAX at that point will be printed on the Teletype-writer. Following Pause 2, the calculation will be repeated or halted according to the setting of the repeat toggle switch. In either case, the values of  $x_{max}$  and  $y_{max}$  will be printed on the Teletypewriter if the print toggle switch is set "up." The values printed are for a range of J as selected on the rotary switches. The subroutine OUTPT accomplishes this printing. Pressing the continue button during Pause 2 resumes the processing according to the options set on the panel.

If the calculation is to be repeated, more input is required. If only the magnetic field strengths for two quadrupoles are to be changed, this can be done from the panel before the continue button is pressed. For changing other parameters, more input through the Teletypewriter is required. A (possibly new) value of JMAX is

input, along with the number of the element whose parameters, and possibly whose type, are to be changed. After the input for an element, the value of the variable AGAIN is set to TRUE if another element is to be changed, and is set to FALSE otherwise. In the program, the subroutine REPET controls the input and repeats the calculation.

When the calculation is halted, either the present case can be dumped or a new calculation can be initiated. Pushbutton D selects the dump. Pushbutton 7 initiates the new calculation, which then requires a new input of the beam parameters.

If a program has been dumped, the calculations can be resumed at a later time. The subroutine RFRESH provides an option for printing out the parameter values currently stored in the program when it is being reloaded from a prior dump. The value of the variable PRINT is entered as TRUE on the Teletypewriter if the printout is wanted, FALSE otherwise.

### Display

The oscilloscope display (fig. 6) consists of

(1) Values of  $x_{max}$  and  $y_{max}$  as function of distance z, where  $x_{max}$  is plotted as a positive value and  $y_{max}$  as a negative value from the centerline (The values are displayed at 10 equally spaced points in each drift space.)

(2) Two horizontal lines, corresponding to the physical beam tube wall, a physical distance of 3.81 centimeters (1.5 in.) from the beam axis

(3) Labels for each element (M,Q,R,T) along with an element index number

(4) A magnified display of the target at the extreme right of the screen (Two fiducial lines each represent a distance of 1 mm from the beam centerline. The  $x_{max}$  and  $y_{max}$  of the beam at the target are displayed at the magnification corresponding to the fiducial lines.)

### Panel

The panel (fig. 5) consists of

(1) Lamps - Lamp 1 being on signals Pause 1 at the beginning of the program. The continue button is used to proceed. Lamp 2 being on signals Pause 2 at the completion of a new calculation and display. The continue button is used to proceed. Lamp 7 being on signals Pause 7 for the selection of the "Dump or go to 1" option. Either the dump or go-to-1 button is used to proceed.

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APPENDIX A  
FORTRAN LISTING FOR PDP-15 VERSION

```
C . . . . .MAIN PRCGRAM FOR BEAM, BEAM TRANSPORT
C
LOGICAL BUTTNS,HALT,TCGGLS,BITEST
COMMON/ADZI/A(6,6,15),DIST(15),ZL(16),IEL
COMMON/ELEM/T/R0(15),PHI(15),ALP(15),BET(15),EL(15),FG(15),
1ALPH(15),IQMR(15)
COMMON/TAX/T(6,6),XMAX(6)
COMMON/SAV/TSV(6,6,15),ZNOT(16)
COMMON/DSPXY/XDSP(150),YDSP(150,2),JMAX
C . . . . .READY, INITIALIZE ARRAYS
101    CALL LAMPON(1)
IBUT=0
110    IF(BUTTNS(IBUT)) GO TO 110
IF(IBUT.LT.128) GO TO 110
CALL ZERO(A)
CALL ZERO(XDSP)
CALL ZERO(YDSP)
CALL LAMPGF(1)
C . . . . . INPUT BEAM,ELEMENT PARAMETERS
CALL INLIST(XMAX,5H XMAX)
CALL INPUT1(JMAX,4HJMAX,1)
DO 115 J=1,JMAX
CALL REED(J)
CALL TOGGLS(ITOG)
IF(.NOT.BITEST(ITOG,10)) GO TO 115
CALL RITE(J)
115    CONTINUE
C . . . . . INITIAL VALUES FOR FIRST CALCULATION
J=1
200    DO 205 M1=1,6
      DO 205 M2=1,6
      T(M1,M2)=0.
205    IF(M1.EQ.M2) T(M1,M2)=1.
C . . . . . BEGIN LOOP FOR TRANSPORT
251    DEL= ZL(J)/10.
IZ=J*10 - 10
ZTOT = ZNOT(J)
IF(J.EQ.1) ZTOT = 0.
252    CALL DRIFT(DEL,ZTOT,IZ)
```

```

DO 255 L=1,6
T(1,L) = T(1,L) + T(2,L)*ZL(J)
T(5,L) = T(5,L) + T(6,I)*ZL(J)
ZTOT = ZTCT + ZL(J)
CALL MATMLT(J)
ZTOT = ZTCT + DIST(J)
JP1 = J+1
ZNCT(JP1) = ZTOT
DO 275 M1=1,6
DO 275 M2=1,6
275 TSV(M1,M2,J) = T(M1,M2)
J = JP1
299 IF(J.LE.JMAX) GO TO 251
C . . . . . END TRANSPORT LOOP
301 CALL DSPLA
CAIL TOGGLS(ITOG)
IF(.NOT.BITEST(ITOG,14)) GC TC 402
400 CALL OUTPT
402 CALL TOGGLS(ITOG)
HALT=.TRUE.
IF(BITEST(ITOG,12)) HALT=.FALSE.
IF(HALT) GO TO 599
500 CALL REPET(JMIN)
J=JMIN
CALL TOGGLS(ITOG)
IF(.NOT.BITEST(ITOG,15)) GO TO 504
CALL CLKOFF
504 IF(J.EQ.1) GO TO 200
JM1 = J-1
DO 505 M1=1,6
DO 505 M2=1,6
505 T(M1,M2) = TSV(M1,M2,JM1)
GO TO 251
599 IB=0
CALL LAMPON(7)
600 IF(BUTTNS(IB)) GO TO 600
IF(IB.NE.16.AND.IB.NE.32) GO TO 600
CALL IAMPWF(7)
IF(IB.EQ.16) GO TO 601
GO TO 101
601 CALL VPSTOP
CALL QDUMF
CALL VPSTRT
CALL RFRESH
GO TO 301
END

```

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COMMON/ADZI/A(6,6,15),DIST(15),ZL(16),IEL  
COMMON/ELEM/T/RO(15),PHI(15),ALF(15),BET(15),EL(15),PG(15),  
1ALPH(15),IQMR(15)

C

```
JW = J
IEL=IQMR(JW)
10   WRITE(6,10) JW,IEL,ZL(J),DIST(J)
      FORMAT(1H0,17H ELEMENT NUMBER =,I1,7H TYPE= ,I1,12H
      PRE-DRIFT= ,1F10.5,11H LENGTH =,F10.5/)
      DO 115 K=1,6
      115  WRITE(6,20) (A(K,N,J),N=1,6)
      CONTINUE
      RETURN
20   FORMAT(1H ,F11.6,5F12.6)
      END
```

SUBROUTINE MAG(J,RC,PHI,ALP,BET)

```
C . . . . COMPUTE MAGNET MATRIX FROM INPUT PARAMETERS
C . . . . COMMON/ADZI/A(6,6,15),DIST(15),ZL(16),IEL
C . . . . SET ELEMENTS USED IN QUAD OR ROT TO ZERO
      A(1,5,J) = 0.
      A(2,6,J) = 0.
      A(5,1,J) = 0.
      A(6,2,J) = 0.
C . . . . COMPUTE SINE AND CCSINE VALUES
      RPI=3.141593/180.
      PR=PHI*RPI
      AR=ALP*RPI
      BR=BET*RPI
      CP=COS(PR)
      CA=COS(AR)
      CB=COS(BR)
      SP=SIN(PR)
      SA=SIN(AR)
      SB=SIN(BR)
      TA=SA/CA
      TB=SB/CB
      A(1,1,J) = CP+SP*TA
      A(1,2,J) = RO*SP
      A(1,3,J) = RO*(1.-CP)
      A(2,1,J) = -SIN(PR-AR-BR)/(RO*CA*CB)
      A(2,2,J) = CP + SP*TB
      A(2,3,J) = SP + (1.-CP)*TB
```

```

A(3,3,J) = 1.
A(4,1,J) = SP + (1.-CP)*TA
A(4,2,J) = RO*(1.-CP)
A(4,3,J) = RO*(PR-SP)
A(4,4,J) = 1.
A(5,5,J) = 1.-PR*TA
A(5,6,J) = PR*RO
A(6,5,J) = (-TA-TB+PR*TA*TB)/RO
A(6,6,J) = 1.-PR*TB
DIST(J) = A(5,6,J)
RETURN
END

```

### SUBROUTINE QUAD(J,EL,FG)

```

C
C . . . . COMPUT QUAD MATRIX FROM INPUT PARAMETERS
COMMON/ADZI/A(6,6,15),DIST(15),ZL(16),IEL
C . . . . . SET ELEMENTS USED IN MAG OR ROT TO ZERO
A(1,3,J) = 0.
A(1,5,J) = 0.
A(2,3,J) = 0.
A(2,6,J) = 0.
A(4,1,J) = 0.
A(4,2,J) = 0.
A(4,3,J) = 0.
A(5,1,J) = 0.
A(6,2,J) = 0.
C . . . . COMPUTE MATRIX ELEMENTS
IF(FG) 100,200,300
100   FG = - FG
      EPL = EXP(FG*EL)
      EMI = EXP(-FG*EL)
      SF = SIN(FG*EL)
      A(1,1,J) = .5*(EPL + EMI)
      A(1,2,J) = (EPL-EMI)/(2.*FG)
      A(2,1,J) = FG*FG*A(1,2,J)
      A(5,5,J) = COS(FG*EL)
      A(5,6,J) = SF/FG
      A(6,5,J) = -FG*SF
      FG = -FG
      GO TO 400
300   SF = SIN(FG*EL)
      EPL = EXP(FG*EL)
      EMI = EXP(-FG*EL)

```

```

A(1,1,J) = COS(FG*EL)
A(1,2,J) = SF/FG
A(2,1,J) = -FG*S傅
A(5,5,J) = .5*(EPL+EMI)
A(5,6,J) = (EPL-EMI)/(2.*FG)
A(6,5,J) = FG*FG*A(5,6,J)
GO TO 400
200 A(1,1,J) = 1.
      A(1,2,J) = EL
      A(2,1,J) = 0.
      A(5,5,J) = 1.
      A(5,6,J) = EL
      A(6,5,J) = 0.
400 A(2,2,J) = A(1,1,J)
      A(3,3,J) = 1.
      A(4,4,J) = 1.
      A(6,6,J) = A(5,5,J)
      DIST(J) = EL
      RETURN
      END

```

```

SUBROUTINE ROT(J,AA)
C
C . . . . COMPUTE ROTATION MATRIX FROM INPUT PARAMATERS
COMMON/ADZI/A(6,6,15),DIST(15),ZL(16),IEL
C . . . . .SET ELEMENTS USED IN MAG OR QUAD TO ZERO
A(1,2,J) = 0.
A(1,3,J) = 0.
A(2,1,J) = 0.
A(2,3,J) = 0.
A(4,1,J) = 0.
A(4,2,J) = 0.
A(4,3,J) = 0.
A(5,6,J) = 0.
A(6,5,J) = 0.
C . . . . .COMPUTE MATRIXELEMENTS
AR = AA*3.141593/180.
CS = CCS(AR)
SN = SIN(AR)
A(1,1,J) = CS
A(1,5,J) = SN
A(2,2,J) = CS
A(2,6,J) = SN
A(5,1,J) = - SN

```

```

A(5,5,J) = CS
A(6,2,J) = -SN
A(6,6,J) = CS
A(4,4,J) = 1.
A(3,3,J) = 1.
DIST(J) = 0.
RETURN
END

```

SUBROUTINE DRIFT(DEL,ZTCT,IZ)

```

C
C . . . . TRANSPORT BEAM THRU DRIFT TUBE, COMPUTE PCSITIONS
DIMENSION SIG1(6,6),SIG2(6,6),XMEX(6)
COMMON/ADZI/A(6,6,15),DIST(15),ZL(16),IEL
COMMON/DSPXY/XDSP(150),YDSP(150,2),JMAX
COMMON/TAX/T(6,6),XMAX(6)
COMMON/SAV/TSV(6,6,15),ZNCT(16)
EQUIVALENCE (A(1,1,15),SIG1(1,1))
EQUIVALENCE (TSV(1,1,15),SIG2(1,1))
ZINT=ZTOT
DO 215 M1=1,6
DO 215 M2=1,6
SIG1(M1,M2)=0.
DO 205 M3=1,6
SIG1(M1,M2)=SIG1(M1,M2)+T(M1,M3)*(XMAX(M3)**2)*T(M2,M3)
205  CONTINUE
SIG2(M1,M2)=SIG1(M1,M2)
215  CONTINUE
DO 255 K1=1,10
DO 225 M1=1,6
SIG2(1,M1)=SIG2(1,M1)+DEL*SIG1(2,M1)
SIG2(5,M1)=SIG2(5,M1)+DEL*SIG1(6,M1)
225  CONTINUE
DO 235 M1=1,6
SIG2(M1,1)=SIG2(M1,1)+DEL*SIG1(M1,2)
SIG2(M1,5)=SIG2(M1,5)+DEL*SIG1(M1,6)
235  CONTINUE
SIG2(1,1)=SIG2(1,1)+(DEL**2)*SIG1(2,2)
SIG2(1,5)=SIG2(1,5)+(DEL**2)*SIG1(2,6)
SIG2(5,1)=SIG2(5,1)+(DEL**2)*SIG1(6,2)
SIG2(5,5)=SIG2(5,5)+(DEL**2)*SIG1(6,6)
IF(IZ.EQ.999) GO TO 260
ZINT=ZINT+DEL
IZ=IZ+1

```

```

YDSP(IZ,1)=SQRT(SIG2(1,1))
XDSP(IZ)=ZINT
YDSP(IZ,2)=SQRT(SIG2(5,5))
DO 245 M1=1,6
DO 245 M2=1,6
SIG1(M1,M2)=SIG2(M1,M2)
245 CONTINUE
255 CONTINUE
RETURN
260 DO 265 ID=1,6
265 XMEX(ID) = SQRT(SIG2(ID,ID))
      WRITE(6,10) (XMEX(IW),IW=1,6)
10   FORMAT(1H0,6HXMEX= ,6(3X,F7.3))
      RETURN
      END

```

#### SUBROUTINE MATMLT(JJ)

```

C
C . . . .ROUTINE FOR MATRIX MULTIPLICATION
DIMENSION C(6,6)
COMMON/ADZI/A(6,6,15),DIST(15),ZL(16),IEL
COMMON/TAX/T(6,6),XMAX(6)
EQUIVALENCE (A(1,1,15),C(1,1))
DO 105 M1=1,6
DO 105 M2=1,6
C(M1,M2)=0.
DO 105 M3=1,6
C(M1,M2)=A(M1,M3,JJ)*T(M3,M2)+C(M1,M2)
105 CONTINUE
DO 115 M1=1,6
DO 115 M2=1,6
T(M1,M2)=C(M1,M2)
115 CONTINUE
RETURN
END

```

#### SUBROUTINE DSPLA

```

C
C.....THIS ROUTINE USES SCOPE DISPLAY
INTEGER XYP(2,320),YPX,YPY,V(5,2),P(2,2),TAGS(4,30)
LOGICAL BUTTNS,PENSH
DIMENSION RJ(15),RL(4)

```

```

COMMON/TAG/RTAGS(2,30),XYP
COMMON/DSPXY/XDSP(150),YDSP(150,2),JMAX
COMMON/ELEMT/RO(15),PHI(15),ALF(15),BET(15),EL(15),PG(15),
1ALPH(15),IQMR(15)
EQUIVALENCE (TAGS(1,1),RTAGS(1,1))
DATA RL(1),RL(2),RL(3),RL(4)/1BM,1HQ,1HR,1HT/
DATA RJ(1),RJ(2),RJ(3),RJ(4),RJ(5),RJ(6),RJ(7),RJ(8),RJ(9),
1RJ(10),RJ(11),RJ(12),RJ(13),RJ(14),RJ(15)/1H1,1H2,1H3,1H4,
2H5,1H6,1H7,1H8,1H9,2H10,2H11,2H12,2H13,2H14,2H15/
C.....Z SCALE, 1 POINT/INCH
C.....VERTICAL SCALE, 1 POINT=0.005 INCH (1.5"=300)
100      NP=JMAX*10
        DO 125 K=1,NP
          KY=2*K
          KX=KY-1
          XYP(2,KX)=512.+200.*YDSP(K,1)
          XYP(2,KY)=512.-200.*YDSP(K,2)
          XPZ=XDSP(K)
          XYP(1,KY)=XPZ
125      XYP(1,KX)=XPZ
          NP2=2*NP
          NX=NP2 + 1
          NY=NX + 1
          XYP(2,NX)= 512. + 1000.*YDSP(NP,1)
          XYP(2,NY)= 512. - 1000.*YDSP(NP,2)
          YPX = XYP(2,NX)
          YPY = XYP(2,NY)
          XYP(1,NX) = 1000
          XYP(1,NY) = 1022
C . . . . .GENERATE 1 MM MARKERS
200      NM1 = NY+1
          NM2 = NM1 + 9
          MM = 40
          NZ = 1010
          DO 225 L=NM1,NM2
            XYP(2,L) = 512 + MM
            XYP(1,L) = NZ
            MM = - MM
225      NZ = NZ + 1
          NP2 = NP2 + 12
          CALL VPPNTS(XYP,NP2,IHIT,1)
C . . . . .GENERATE BCUNDARIES AT +1.5", -1.5"
300      MINUS = -1
          DO 325 LL=1,2
            P(1,1) = 0
            P(1,2) = 950

```

```

MP = 512 + MINUS*300
P(2,1) = MP
P(2,2) = MP
CALL VECTCR(P,V,LL)
325 MINUS = - MINUS
390 CALL VPVECT(V,2,IH,2)
400 MQ = 1
DO 455 J=1,JMAX
JE = 2*J
JO = JE-1
RTAGS(1,JO) = RJ(J)
K = (IQMR(J) + 1) / 2
RTAGS(1,JE) = RL(K)
410 J10 = 10*J
TAGS(3,JO) = XDSP(J10)
TAGS(3,JE) = XDSP(J10)
IF(IQMR(J).NE.3) GO TO 420
MQLO = 0
IF(MQ.EQ.-1) MQLO = 30
TAGS(4,JO) = 512 + MQ*(305 + MOLO)
TAGS(4,JE) = 512 + MQ*(305 + 30 + MQLO)
MQ = - MQ
GO TO 455
420 TAGS(4,JO) = 512 + 305
TAGS(4,JE) = 512 + 305 + 30
455 CONTINUE
NT = JMAX * 2
490 CALL VPTAGS(TAGS,NT,IT,3)
500 CALL VPSTRT
CALL CLKON
IF(YPX.GT.552.OR.YPY.IT.472) GO TO 526
DO 525 LA=1,7
525 CALL LAMPON(LA)
526 CALL LAMPCN(2)
IBUT=0
530 IF(PENSW(.TRUE.)) GO TO 600
IF(BUTTNS(IBUT)) GO TO 530
IF(IBUT.LT.128) GO TO 530
DO 535 LA=1,7
535 CALL LAMPCF(LA)
RETURN
600 NH=(IINIT+1)/2
CALL LANDT(NH)
GO TO 530
END

```

SUBROUTINE OUTPT

```
C  
C . . . . WRITE OUT DISPLAY POINTS  
COMMON/DSPXY/XDSP(150),YDSP(150,2),JMAX  
WRITE(6,10)  
10 FORMAT(1H0,5X,45HX AND Y BEAMCCCRDSASFUNCTIONOFDISTANCE Z/)  
J3 = IROTOR(3)  
J4 = IROTOR(4)  
JBGN = 10*J3 - 9  
JEND = 10*J4  
IF(JEND.GT.140) JEND=140  
DO 115 J1=JBGN,JEND,10  
J2=J1+9  
WRITE(6,20)(YDSP(JX,1),JX=J1,J2)  
20 FORMAT(2H X,10F7.3)  
WRITE(6,30)(XDSP(JZ),JZ=J1,J2)  
30 FORMAT(1H ,10F7.2)  
WRITE(6,40)(YDSP(JY,2),JY=J1,J2)  
40 FORMAT(2H Y,10F7.3///)  
115 CONTINUE  
RETURN  
END
```

SUBROUTINE REPET(JMIN)

```
C  
C . . . .CHANGES SPECIFIED ELEMENTS AND REPEATS TRANSPORT  
LOGICAL AGAIN,TOGGLS,EITEST  
COMMON/ELEMT/RO(15),PHI(15),ALP(15),RET(15),EL(15),FG(15),  
1ALPH(15),IQMR(15)  
COMMON/DSPXY/XDSP(150),YDSP(150,2),JMAX  
C  
C . . . .IF TOGGL 11 IS SET, GET NEW QUAD CURRENT FROM THUMB  
CAII TOGGIS(ITOG)  
IF(.NOT.BITEST(ITOG,11)) GC TC 301  
J1=IROTOR(1)  
J2=IFOTOR(2)  
JMIN = J1  
IF(J2.LT.J1) JMIN=J2  
IFG1=ITHUMB(1)  
IFG2=ITHUMB(2)  
FG1=FLOAT(IFG1)*0.00001  
FG2=FLOAT(IFG2)*0.00001  
IF(BITEST(ITOG,13)) FG1=-FG1  
IF(BITEST(ITOG,17)) FG2=-FG2
```

```

FG(J1) = FG1
FG(J2) = FG2
EL1=EL(J1)
EL2=EL(J2)
10   WRITE(6,10) J1,FG1,J2,FG2
      FORMAT(1H0,6HJ, FG,5X,2(I2,F10.5))
      CALL QUAD(J1,EL1,FG1)
      CALL QUAD(J2,EL2,FG2)
      IF(.NOT.BITEST(ITOG,10)) GO TO 500
      CALL RITE(J1)
      CALL RITE(J2)
      GO TO 500
C
C . . . . INPUT ELEMENT PARAMETERS THRU TELETYPE
301   CALL INPUT1(JMAX,4HJMAX,1)
      JMIN = JMAX
302   CALL INPUT1(JJ,5HNELEM,1)
      IF(JJ.LT.JMIN) JMIN=JJ
      CALL REED(JJ)
      CALL TOGLS(ITOG)
      IF(.NOT.BITEST(ITOG,10)) GO TO 303
      CALL RITE(JJ)
303   CALL INPUT1(AGAIN,5HAGAIN,4)
      IF(AGAIN) GO TO 302
500   RETURN
      END

```

#### SUBROUTINE RFRESH

```

C
C . . . . . WRITE PARAMETERS AFTER RESTART FROM PREVIOUS DUMP
LOGICAL PRINP
COMMON/ELEMT/RO(15),PHI(15),ALP(15),BET(15),EL(15),FG(15),
1ALPH(15),IQMR(15)
COMMON/ADZI/A(6,6,15),DIST(15),ZL(16),IEL
COMMON/DSPXY/XDSP(150),YDSP(150,2),JMAX
C
20   WRITE(6,20)
      FORMAT(42H0 DO YOU WISH TO PRINT CURRENT PARAMETERS?)
      CALL INPUT1(PRINP,5HPRINT,4)
      IF(.NCT.PRINP) GO TO 500
      DO 295 L=1,JMAX
      LW=L
      WRITE(6,40) LW,IQMR(L),ZL(L),DIST(L)
40   FORMAT(1H0,17H ELEMENT NUMBER =,I2,6H TYPE ,I1,12H
      PRE-DRIFT= ,

```

```

1F10.2,11H LENGTH=,F10.2)
IW=IQMR(L)
GO TO (231,231,233,233,235,235,500),IW
231 10 WRITE(6,10) RO(L),PHI(L),AIE(L),BET(L)
      FORMAT(1H0,6HRHO =,F10.2,6HPHI =,F10.2,8HALPHA=,F10.2,7H BE
      1TA =,F10.2/)
      GO TO 295
233 30 WRITE(6,30) PG(L)
      FORMAT(1H0,11H FLD GRAD =,F10.5/)
      GO TO 295
235 50 WRITE(6,50) ALPH(L)
      FORMAT(1H0,17H ROTATION ANGLE =,F10.2/)
295 295 CONTINUE
500 500 RETURN
END

```

#### SUBROUTINE LANDT(NH)

```

C
C . . . . . CALCULATE L FROM XMAX; CALCULATE T MATRIX
COMMON/ADZI/A(6,6,15),DIST(15),ZL(16),IEL
COMMON/TAX/T(6,6),XMAX(6)
COMMON/ELEM/T(15),RO(15),PHI(15),ALP(15),BET(15),EL(15),FG(15),
1ALPH(15),IQMR(15)
COMMON/SAV/TSV(6,6,15),ZNCT(16)
C . . . . . JH IS INDEX FOR HIT
100   JH=(NH-1)/10+1
      JHM1 = JH - 1
      DEL=ZL(JH)/10.
      IZL= NH-JHM1*10
      ZLH = DEL*FLOAT(IZL)
      IF(JH.NE.1) GO TO 250
C . . . . . SET UP SPECIAL CASE FOR JH=1
      JHM1=15
210   DO 215 M1=1,6
      DO 215 M2=1,6
      TSV(M1,M2,15) = 0.
215   IF(M1.EQ.M2) TSV(M1,M2,15) = 1.
C . . . . . STORE TRANSPORT MATRIX IN A(I,M,15)
250   DO 255 L=1,6
      A(1,L,15) = TSV(1,L,JHM1) + TSV(2,L,JHM1)*ZLH
      A(2,L,15) = TSV(2,L,JHM1)
      A(3,L,15) = TSV(3,L,JHM1)
      A(4,L,15) = TSV(4,L,JHM1)
      A(5,L,15) = TSV(5,L,JHM1) + TSV(6,L,JHM1)*ZLH

```

```
255      A(6,L,15) = TSV(6,L,JHM1)
C . . . . .SET UP PARAMETERS FOR CALL TO RITE
DIST(15) = ZLH
IQMR(15) = 9
ZL(15) = ZLH
IP(JH.NE.1) ZL(15) = ZL(15)+ZNOT(JH)
CALL RITE(15)
C . . . . .SET UP T MATRIX FOR CALL TO DRIFT
DO 305 M1=1,6
DO 305 M2=1,6
305  T(M1,M2) = TSV(M1,M2,JHM1)
DEL=ZIH
CALL DRIFT(DEL,0.,999)
RETURN
END
```

## APPENDIX B

### IBM 7094 VERSION OF BEAMR

The IBM 7094 version of the BEAMR program is similar to that just described except that there exists no interactive mode and no facility for display of results. Rather, the program supplies printed description of the beam and cumulative values for the transfer matrix at points specified. In addition, the program will automatically search to determine what values of the quadrupole focusing strength are required to obtain preset values for two elements of the total transfer matrix at a preset position.

The input for the program is as follows:

CARD NUMBER	FORMAT	INFORMATION
1	13A6	Title
2	6F10.0	$x_{\max}$ , $x'_{\max}$ , $\Delta p/p$ , $\Delta\lambda$ , $y_{\max}$ , $y'_{\max}$
3	2I2	JMIX, JMOX
4	1F10.0	DELK
5	5F10.0,I1	P1, P2, P3, P4, P5, XJ
-	-	-
-	-	-
-	-	-
4+JMIX	-	-
4+JMIX+1	4I3, 4E15.8, 2I3	AI, AJ, BI, BJ, SFOC1, SFOC2, VAL1, VAL2, J1, J2 (This card only for JMOX=1.)

#### Definitions of Input

The parameters  $x_{\max}$ ,  $x'_{\max}$ ,  $\Delta p/p$ ,  $\Delta\lambda$ ,  $y_{\max}$ ,  $y'_{\max}$  are characteristics of the beam at the entrance to the system, as defined previously, in inches and radians. JMIX is the total number of beam-handling elements in the system, including drift spaces. JMOX specifies search procedures: 0, no search; 1, search on quadrupole strengths.

The total transfer matrix and the maximum beam dimensions in the drift space beyond the last beam-handling element will be calculated and printed out 25 times

if so desired. These calculations will be done at intervals DELK (in.) from the exit of this element.

The definitions of P1, P2, P3, P4, and P5 vary depending on the type of beam-handling element involved. The type of element is defined by XJ:

For a magnet, XJ=1:

P1      radius of curvature  
P2      angle of deflection  
P3      entrance edge angle  
P4      exit edge angle  
P5      PL

For a drift space, XJ=2:

P1      length of drift space  
P2      0  
P3      0  
P4      0  
P5      0

For a quadrupole magnet, XJ=3,:  
P1      effective length of quadrupole  
P2      strength, k - positive for horizontal focusing, negative for vertical focusing  
P3      PL  
P4      0  
P5      0

For a quadrupole (part of a symmetric triplet), XJ=4: P1,P2,P3,P4, and P5 are the same as for XJ=3. For a rotation, XJ=5: P1 is the magnitude and direction of the rotation - positive for a clockwise rotation, negative for a counterclockwise rotation.

The quantity PL defines, for each beam-handling element, whether a description of the beam for the drift space following the element will be printed out. If PL = 1, the drift space following the element will be divided into 20 equal intervals and a description of the beam (total  $\mathcal{T}$  matrix and maximum beam dimensions) will be printed as calculated at the end of each interval. If PL = 0, no output is printed.

The quantities AI,AJ,BI,BJ,SFOC1,SFOC2,VAL1,VAL2,J1, and J2 specify search procedures. The search routine will attempt to adjust the strengths of quadrupoles J1 and J2 so as to produce, at a distance SFOC1 beyond the last element, the value VAL1 for the transfer matrix element T(AI,AJ). Simultaneously, it will attempt

to produce at the distance SFOC2 beyond the last element the value VAL2 for the transfer matrix element T(BI,BJ).

If one of the quadrupoles specified is the first section of a symmetric triplet (XJ=4), the focusing strength of the last section of the triplet will be held identically equal to that of the first section during all search procedures.

The search routine optimizes the specified parameters by first constructing numerically the gradients

$$\begin{array}{ll} \frac{\partial T(AI, AJ)}{\partial k(J1)} & \frac{\partial T(AI, AJ)}{\partial k(J2)} \\[10pt] \frac{\partial T(BI, BJ)}{\partial k(J1)} & \frac{\partial T(BI, BJ)}{\partial k(J2)} \end{array}$$

and then solving the equations

$$\begin{aligned} \Delta T(AI, AJ) &= \left[ \frac{\partial T(AI, AJ)}{\partial k(J1)} \right] \Delta k(J1) + \left[ \frac{\partial T(AI, AJ)}{\partial k(J2)} \right] \Delta k(J2) \\ \Delta T(BI, BJ) &= \left[ \frac{\partial T(BI, BJ)}{\partial k(J1)} \right] \Delta k(J1) + \left[ \frac{\partial T(BI, BJ)}{\partial k(J2)} \right] \Delta k(J2) \end{aligned}$$

for corrections  $\Delta k$  to the field gradients. The quantity  $\Delta T(AI, AJ)$  is the difference between the current value of the (AI,AJ) matrix element and the desired value VAL1.

## **APPENDIX C**

### **FORTRAN LISTING OF IBM 7094 VERSION**

SIPFTC BEAMR DECK

BEAMR DOES BEAM TRANSPORT CALCULATIONS IN FIRST ORDER, USING A BEAM TRANSFER MATRIX. IT TREATS MAGNETS, DRIFT SPACES, QUADRUPOLE LENSES, AND ROTATIONS.

INPUT IS AS FOLLOWS

CARD ONE CONTAINS A TITLE

CARD 2 (6F10.0) CONTAINS A DESCRIPTION OF THE BEAM AT THE SYSTEM ENTRANCE

- A) MAXIMUM SIZE OF BEAM IN THE X-DIRECTION (INCHES)
- B) MAXIMUM DIVERGENCE OF THE BEAM IN THE X PLANE (RADIAN)
- C) INCIDENT MOMENTUM SPREAD (FRACTIONAL)
- D) MAXIMUM SPREAD IN PATH LENGTH ENTERING THE SYSTEM (INCHES)
- E) MAXIMUM EXTENSION OF THE BEAM IN THE Y DIRECTION (INCHES)
- F) MAXIMUM DIVERGENCE OF THE BEAM IN THE Y PLANE (RADIAN)

CARD 3 (FORMAT 2I2) CONTAINS JMIX AND JMOX

JMIX IS THE TOTAL NUMBER OF ELEMENTS (DRIFT SPACES, QUADRUPOLE SINGLTS, MAGNETS, RCTATICNS) IN THE EAM LINE

JMOX SPECIFIES SEARCE PROCEDURES

JMOX=0 IMPLIES NO SEARCH

JMOX=1 IMPLIES SEARCHING ON QUADRUPOLE CURRENTS

CARD 4 (1F10.0) CONTAINS THE QUANTITY DELK (INCHES)

CARDS 5 TO 5+JMIX (5F10.0, 1I1) DESCRIBE INDIVIDUAL BEAM ELEMENTS, ONE CARD PER ELEMENT

MAGNET- COL1-10 CONTAIN THE RADIUS OF CURVATURE (GREATER THAN ZERO)

COL 11-20 CONTAIN THE ANGLE OF DEFLECTION (GREATER THAN ZERO)

COL 21-30 CONTAIN THE ENTRANCE ANGLE (POSITIVE ANGLES YIELD VERTICAL FOCUSING)

COL 31-40 CONTAIN THE EXIT ANGLE ( POSITIVE ANGLES YIELD VERTICAL FOCUSING)

COL 41-50 CONTAIN PI

COL 51 CONTAINS XJ (SHOULD EQUAL 1 FOR A MAGNET)

THE ABOVE SIGN CONVENTIONS ARE FOR A MAGNET WHICH BENDS TO THE RIGHT. FOR A LEFT-BENDING MAGNET ALL SIGNS ARE REVERSED.

QUADRUPOLE COL 1-10 EFFECTIVE LENGTH OF THE QUAD (INCHES)

COL 11-20 CONTAIN K, WHERE K IS THE QUADRUPOLE

```

C      STRENGTH DEFINED BY
C          K=SQRT(FIELD GRADIENT (KG/INCH)/BR (KG-INCHES))
C          POSITIVE K YIELDS X-FOCUS, Y-DEFOCUS
C          NEGATIVE K YIELDS X-DEFOCUS, Y-FOCUS
C      COL 21-30 CONTAIN PL
C      COL 51 CCNTAINS XJ (SHOULD BE 3 FOR A QUADRUPOLE)
C          IF COL 51 CONTAINS A 4 IT INDICATES THAT THE ELEMENT
C          BEING DESCRIBED IS TO BE CONSIDERED AS THE FIRST
C          SECTION OF A SYMMETRIC TRIPLET, AND IN ANY SEARCH
C          PROCEDURE THE LAST ELEMENT OF THE TRIPLET WILL ALWAYS
C          HAVE A STRENGTH EQUAL TO THIS ONE
C      DRIFT SPACE COL 1-10 LENGTH CF THE DRIFT (INCHES)
C          COL 11-21 PL (SHOULD BE ZERO)
C          COL 51 XJ (SHOULD BE 2 FOR A DRIFT SPACE)
C      ROTATION, COL1-10 CONTAIN THE MAGNITUDE OF THE ROTATION
C          IN DEGREES. . A POSITIVE ROTATION INDICATES A
C          DOWNWARD BEND, A NEGATIVE ROTATION INDICATES
C          AN UPWARD EEND
C          COL 17-20 CONTAIN PL
C          COL 51 CONTAINS XJ (SHOULD BE 5 FOR A ROTATION)
C          FOR ANY ELEMENT, SETTING PL=1 CAUSES THE TRANSFER MATRIX TO BE
C          PRINTED OUT AT INTERVALS OF DELTA INCHES BEYOND THE GIVEN
C          ELEMENT, WHERE DELTA=1/20 OF THE FCLOWING DRIFT SPACE. FOR THE
C          LAST ELEMENT THE TRANSFER MATRIX IS PRINTED OUT 25 TIMES IN
C          INTERVALS OF DELK.
C          IF PL=0, THE TRANSFER MATRIX IS NOT PRINTED AT THE EXIT OF
C          THE GIVEN ELEMENT.
C      LAST CARD (4I3,4E15.8,2I3)
C      CONTAINS AI,AJ,BI,BJ,SFOC1,SFOC2,VAL1,VAL2,J1,J2.
C      THE SEARCH ROUTINE WILL ATTEMPT TO VARY THE STRENGTHS OF THE
C      J1-TH AND J2-TH QUADRUPOLES IN ORDER TO MAKE THE (AI,AJ)
C      AND (PI,EJ) ELEMENTS OF THE TRANSFER MATRIX EQUAL TO THE VALUES
C      VAL1 AND VAL2 RESPECTIVELY AT DISTANCES SFOC1 AND SFOC2
C      RESPECTIVELY BEYOND THE LAST BEAM ELEMENT.

      INTEGER X,F
      DIMENSION X(50),RO(50),PHI(50),ALP(50),BET(50),ALPR(50),PHIR(50),-
1BETR(50),A(6,6,50),Z(50),T(6,6),TITLE(13),BINT1(3),BINT2(3),-
2FG(50),EL(50),GRAD(2,2),TINT1(6,6,3),TINT2(6,6,3),PL(50),ALPH(50),-
3 ALPHR(50),A1(6,6),A2(6,6),XMAX(6),AC(5,50)
      COMMON A,T,XMAX

100 READ(5,1) TITLE
      READ(5,2) (XMAX(I),I=1,6)
      READ(5,3) JMIX,JMOX
      READ(5,2) DELK

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```
ALPHR (J)=ALPH (J)*3.14159265/180.  
A (1,1,J)=COS (ALPHR (J))  
A (1,5,J)=SIN (ALPHR (J))  
A (2,2,J)=COS (ALPHR (J))  
A (2,6,J)=SIN (ALPHR (J))  
A (5,1,J)=-SIN (ALPHR (J))  
A (5,5,J)=COS (ALPHR (J))  
A (6,2,J)=-SIN (ALPHR (J))  
A (6,6,J)=COS (ALPHR (J))  
A (4,4,J)=1.0  
A (3,3,J)=1.0  
WRITE (6,15) J,ALPH (J)  
  
199 WRITE (6,10) (A (1,N,J),N=1,6)  
WRITE (6,10) (A (2,N,J),N=1,6)  
WRITE (6,10) (A (3,N,J),N=1,6)  
WRITE (6,10) (A (4,N,J),N=1,6)  
WRITE (6,10) (A (5,N,J),N=1,6)  
WRITE (6,10) (A (6,N,J),N=1,6)  
200 CONTINUE  
  
203 DO 201 M1=1,6  
DO 201 M2=1,6  
T(M1,M2)=A(M1,M2,1)  
201 CONTINUE  
  
DO 300 J=2,JMIX  
CALL MATMLT (J)  
IF (X (JMAX).NE.0) GO TO 300  
IF (PL (J).EQ.0.0) GO TO 300  
WRITE (6,14) J,X (J)  
DEL=(Z (J+1)/20.0)+1.0  
IDEL=DEL  
DEL=IDEL  
IF (J+1.EQ.JMAX) DEL=DELK  
CALL EXIT (DEL)  
300 CONTINUE  
  
401 IF (X (JMAX)) 100,100,998  
998 IF (F-2) 999,1000,1000  
999 IF (ZX) 9995,9995,1000  
9995 READ(5,11) IA,JA,IB,JB,SFOC1,SFCC2,VAL1,VAL2,J1,J2  
WRITE (6,11) IA,JA,IP,JB,SFOC1,SFCC2,VAL1,VAL2,J1,J2  
  
1000 A1 (1,1)=1.0
```

```

A1(1,2)=SFOC1
A1(2,2)=1.0
A1(3,3)=1.0
A1(4,4)=1.0
A1(5,5)=1.0
A1(5,6)=SFOC1
A1(6,6)=1.0

DO 1001 L1=1,6
DO 1001 L2=1,6
TINT1(L1,L2,F)=0.0
DO 1001 L3=1,6
TINT1(L1,L2,F)=TINT1(L1,L2,F)+A1(L1,L3)*T(L3,L2)

1001 CONTINUE
WRITE(6,75) F,(TINT1(1,N1,F),N1=1,6)
WRITE(6,75) F,(TINT1(2,N1,F),N1=1,6)
WRITE(6,75) F,(TINT1(3,N1,F),N1=1,6)
WRITE(6,75) F,(TINT1(4,N1,F),N1=1,6)
WRITE(6,75) F,(TINT1(5,N1,F),N1=1,6)
WRITE(6,75) F,(TINT1(6,N1,F),N1=1,6)
A2(1,1)=1.0
A2(1,2)=SFOC2
A2(2,2)=1.0
A2(3,3)=1.0
A2(4,4)=1.0
A2(5,5)=1.0
A2(5,6)=SFOC2
A2(6,6)=1.0

DO 21002 K1=1,6
DO 21002 K2=1,6
TINT2(K1,K2,F)=0.0
DO 21002 K3=1,6
TINT2(K1,K2,F)=TINT2(K1,K2,F)+A2(K1,K3)*T(K3,K2)

21002 CONTINUE
WRITE(6,75) F,(TINT2(1,N1,F),N1=1,6)
WRITE(6,75) F,(TINT2(2,N1,F),N1=1,6)
WRITE(6,75) F,(TINT2(3,N1,F),N1=1,6)
WRITE(6,75) F,(TINT2(4,N1,F),N1=1,6)
WRITE(6,75) F,(TINT2(5,N1,F),N1=1,6)
WRITE(6,75) F,(TINT2(6,N1,F),N1=1,6)

2000 DIFF1=VAL1-TINT1(IA,JA,1)
DIFF2=VAL2-TINT2(IB,JB,1)

```

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```
7 FORMAT(/,3H J=,I2,3X,4HRHO=,1F10.4,3X,4HPHI=,F10.4,3X,6HALPHA=,
1F10.4,3X,5HEFTA=,F10.4)
8 FORMAT(/,3H J=,I2,3X,7H DRIFT=,F10.4)
9 FORMAT(/,3H J=,I2,3X,17HEFFECTIVE LENGTH=,F10.4,5X,2HK=,F10.4)
10 FORMAT(10X,6E15.6)
11 FORMAT(4I3,4E15.6,2I3)
12 FORMAT(10X,8H G(1,1)=,1PE15.6,5X,8H G(1,2)=,1PE15.6)
13 FORMAT(10X,8H G(2,1)=,1PE15.6,5X,8H G(2,2)=,1PE15.6)
14 FORMAT(1H1,1X,2HJ=,I2,5X,5HX(J)=,I1)
15 FORMAT(/,3H J=,I2,3X,11HROTATION OF,1F8.3,7HDEGREES)
16 FORMAT(5F10.5,I1)
75 FORMAT(1X,2HF=,1I2,6E15.6)
END
```

```
$IEFTC QUAD6 DECK
SUBROUTINE QUAD(J,EL,FG)
DIMENSION A(6,6,50),T(6,6),XMAX(6)
COMMON A,T,XMAX
IF(FG) 100,200,300
100 FG=-FG
A(1,1,J)=0.50*(EXP(FG*EL)+EXP(-FG*EL))
A(1,2,J)=(EXP(FG*EL)-EXP(-EL*FG))/(2.0*FG)
A(1,3,J)=0.0
A(2,1,J)=FG*FG*A(1,2,J)
A(2,2,J)=A(1,1,J)
A(2,3,J)=0.0
A(3,3,J)=1.0
A(4,4,J)=1.0
A(5,5,J)=COS(FG*EL)
A(5,6,J)=SIN(FG*EL)/FG
A(6,5,J)=-FG*SIN(FG*EL)
A(6,6,J)=A(5,5,J)
FG=-FG
GO TO 400
300 A(1,1,J)=COS(FG*EL)
A(1,2,J)=SIN(EL*FG)/FG
A(2,1,J)=-FG*SIN(FG*EL)
A(2,2,J)=A(1,1,J)
A(3,3,J)=1.0
A(4,4,J)=1.0
A(5,5,J)=0.50*(EXP(EL*FG)+EXP(-EL*FG))
A(5,6,J)=(EXP(FG*EL)-EXP(-FG*EL))/(2.0*FG)
```

```

A(6,5,J)=FG*FG*A(5,6,J)
A(6,6,J)=A(5,5,J)
GO TO 400
200 A(1,1,J)=1.0
A(1,2,J)=EL
A(1,3,J)=0.0
A(2,2,J)=1.0
A(3,3,J)=1.0
A(4,4,J)=1.0
A(5,5,J)=1.0
A(5,6,J)=EL
A(6,6,J)=1.0
GO TO 400
400 RETURN
END

```

```

$IBFTC EXITU DECK
SUBROUTINE EXIT(DEL)
COMMON A,T,XMAX
DIMENSION A(6,6,50),T(6,6),TLAST(6,6),AL(6,6),XMAX(6),SIGM(6,6),
1 SIG1(6,6),XMF(6),TLT(6,6)
WRITE(6,1) DEL
DO 200 N=1,25
Y=N-1
XL=Y*DEL
AL(1,1)=1.0
AL(1,2)=XL
AL(2,2)=1.0
AL(3,3)=1.0
AL(4,4)=1.0
AL(5,5)=1.0
AL(5,6)=XL
AL(6,6)=1.0
DO 101 I1=1,6
DO 101 I2=1,6
TLAST(I1,I2)=0.0
DO 101 I3=1,6
TLAST(I1,I2)=TLAST(I1,I2)+AL(I1,I3)*T(I3,I2)
101 CONTINUE
WRITE(6,3)
WRITE(6,4) XL,(TLAST(1,K),K=1,6)
WRITE(6,5) (TLAST(2,K),K=1,6)

```

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```
C(M1,M2)=A(M1,M3,JJ)*T(M3,M2)+C(M1,M2)
100 CONTINUE
DO 101 M1=1,6
DO 101 M2=1,6
T(M1,M2)=C(M1,M2)
101 CONTINUE
RETURN.
END
```

```
$IEFTC MAG6      DECK
SUBROUTINE MAG(J,RO,PHI,ALP,BET)
COMMON A,T,XMAX
DIMENSION A(6,6,50),T(6,6),XMAX(6)
PHIR=PHI*3.14159265/180.
ALPR=ALP*3.14159265/180.
BETR=BET*3.14159265/180.
A(1,1,J)=COS(PHIR-ALPR)/COS(ALPR)
A(1,2,J)=RC*SIN(PHIR)
A(1,3,J)=RO*(1.0-COS(PHIR))
A(2,1,J)=-SIN(PHIR-ALPR-BETR)/(RO*COS(ALPR)*COS(BETR))
A(2,2,J)=COS(PHIR-BETR)/COS(BETR)
A(2,3,J)=SIN(PHIR)+(1.0-COS(PHIR))*TAN(BETR)
A(3,3,J)=1.0
A(4,1,J)=SIN(PHIR)+(1.0-COS(PHIR))*TAN(ALPR)
A(4,2,J)=RC*(1.0-COS(PHIR))
A(4,3,J)=RO*(PHIR-SIN(PHIR))
A(4,4,J)=1.0
A(5,5,J)=1.0-PHIR*TAN(ALPR)
A(5,6,J)=PHIR*RO
A(6,5,J)=(-TAN(ALPR)-TAN(BETR)+EHT*TAN(ALPR)*TAN(BETR))/RO
A(6,6,J)=1.0-PHIR*TAN(BETR)
RETURN
END
```

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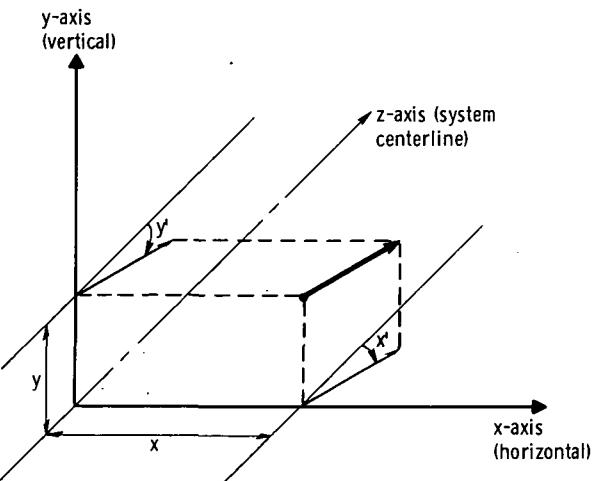


Figure 1. - Coordinate system used for BEAMR.

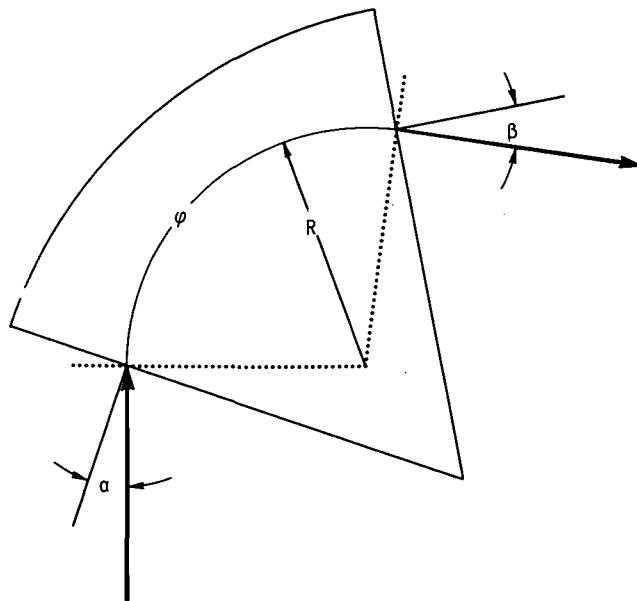


Figure 2. - Magnet dimensions. For right-bending magnet,  $R$  and  $\varphi$  are positive.  $\alpha$  and  $\beta$  (angles between beam and normal to pole face) are positive if (as shown here) center of curvature falls within magnet, negative if it falls outside.

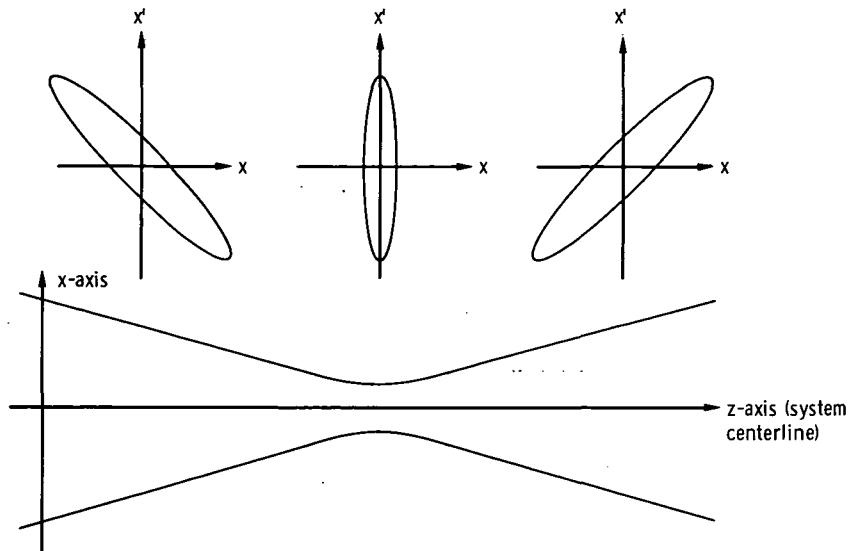


Figure 3. - Evolution of one-dimensional phase-space ellipse as beam envelope passes through a waist. Lower diagram indicates physical size of beam envelope over corresponding interval.

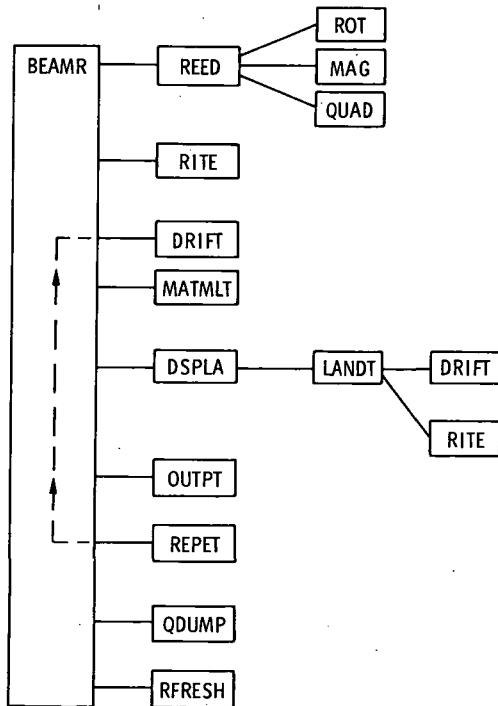


Figure 4. - Schematic of PDP-15 program flow.

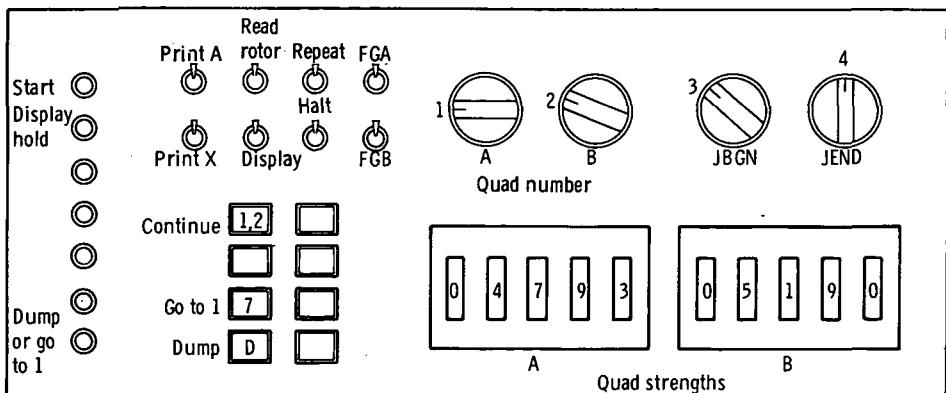


Figure 5. - Functional control panel.

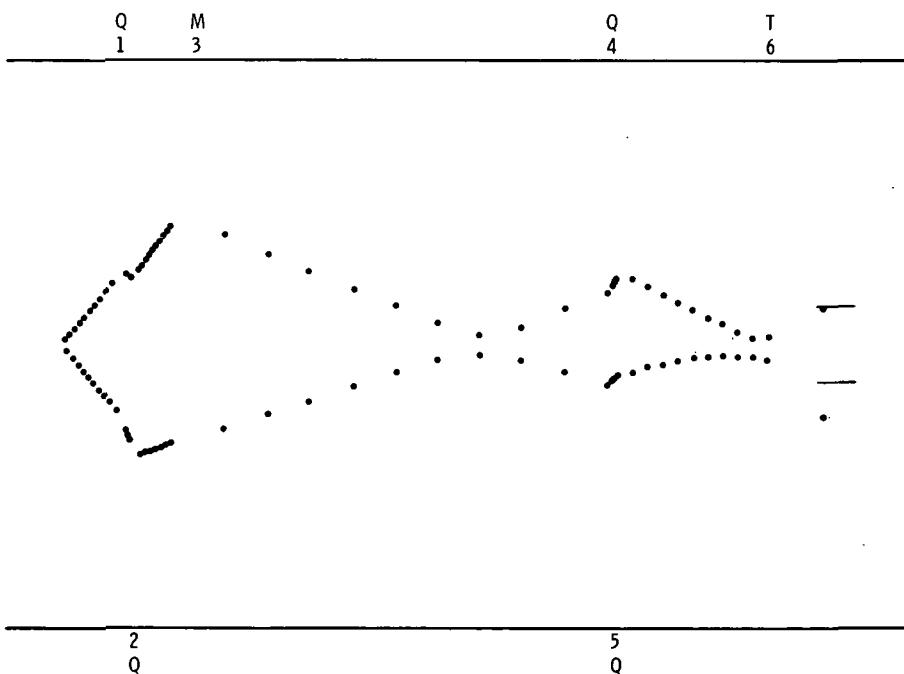


Figure 6. - Typical PDP-15 display of output from BEAMR. System features two sets of quadrupole doublets with a dipole magnet between them.

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